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Speed Regulation and Torque Ripple Minimization of Induction Motor by DTC with PI and Fuzzy Logic Controller

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ABSTRACT

This paper presents a direct flux and torque control (DTC) of Induction motor drive (IMD) for speed regulator (SR) using PI and fuzzy logic controller (FLC). The DTC control method has been optimized by using conventional PI controller in the SR loop of IDM. The main drawback of the DTC of IMD using conventional PI controller based SR is high torque, stator flux ripples and speed of IMD is decreasing under transient and steady state operating conditions. This drawback was eliminated using the FLC. The FLC based SR control scheme combines the benefits of DTC technique along with PI and FLC technique. Finally the effectiveness, validity, and performance of the DTC of IMD using both conventional PI and FL controller based SR has been analyzed, studied, compared, and confirmed by simulation result, from the simulation result found that the low torque, stator flux ripples, and rated speed with the FLC technique using Matlab / simulink.

Keywords – Conventional PI Controller, Direct Torque Control, Fuzzy Logic Controller, Induction Motor Drive, Space Vector Modulation

I. INTRODUCTION

DIRECT torque control (DTC) of induction motors has gained popularity in industrial applications mainly due to its simple control structure from its first introduction in 1986 [1]. The speed of an induction motor depend on the frequency of the supply voltage 50Hz and the speed can only be controlled by varying the frequency, the way to do it is to rectify the AC to DC and convert it back to AC but with another frequency. An electronic speed control is an electronic circuit with the purpose to vary an electric motor's speed, its direction and possibly also to act as a dynamic brake.

Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the flux and torque errors will return in their tolerant bands as fast as possible. Thus direct torque control is one form of the hysteresis or bang-bang control. In the conventional DTC using PI based SR, there are more disadvantages, such as, variable switching frequency, high torque and flux ripple, problem during starting and low speed operating conditions, and flux and current distortion caused by stator flux vector changing with the sector position, in those most important is the speed of IMD is changing under transient state to steady state operating condition [9]. this drawback was eliminated using fuzzy logic control speed regulator instead of conventional PI speed regulator [10].

II. MATHEMATICAL MODEL OF INDUCTION MOTOR

The mathematical model of induction motor drives when the motor is operating in both the steady state and transient states. The standard IMD equivalent model can be used to calculate motor variables such as developed torque, flux, stator voltage, stator current, and rotor current, etc. The induction motor can be modelled with stator current and flux in reference (d^S-q^S) as state variable expressed as follows.

$$x(t) = Ax(t)+Bu_s(t) \quad (1)$$

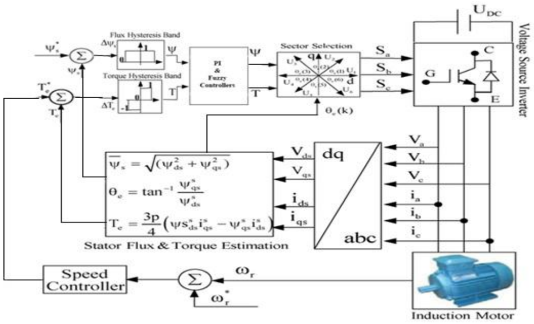
$$y(t) = Cx(t) \quad (2)$$

Where A is System matrix, B is the control and C is the observation, and X(t) is the state variable, u(t) is input vector and Y(t) is output vector. An improved method of speed estimation that operates on the principle of a speed adaptive flux observer. An observer is basically an estimator that uses a plant model and a feedback loop with measured plant variables. The machine model in d^S- q^S frame, where the state flux variables are Ψ^s_{ds} and Ψ^s_{qs} and stator currents and [11].

$$Y(t)=[\ i_{ds}\ i_{qs}\ ]^T \quad (3)$$

$$X(t)= [\ i^s_{ds}\ i^s_{qs}\ \Psi^s_{ds}\ \Psi^s_{qs}\ ]^T \quad (4)$$

$$U_s(t)=[\ U^s_{ds}\ U^s_{qs}\ 0\ 0\ ]^T \quad (5)$$



.Fig 1. Schematic diagram of direct torque control of induction motor drive.

III. DIRECT TORQUE AND FLUX CONTROL

Direct torque control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor.

The direct torque method performs very well even without speed sensors. However, the flux estimation is usually based on the integration of the motor phase voltages. Due to the inevitable errors in the voltage measurement and stator resistance estimate the integrals tend to become erroneous at low speed. Thus it is not possible to control the motor if the output frequency of the variable frequency drive is zero. However, by careful design of the control system it is possible to have the minimum frequency in the range 0.5 Hz to 1 Hz that is enough to make possible to start an induction motor with full torque from a standstill situation. A reversal of the rotation direction is possible too if the speed is passing through the zero range rapidly enough to prevent excessive flux estimate deviation. If continuous operation at low speeds including zero frequency operation is required, a speed or position sensor can be added to the DTC system. With the sensor, high accuracy of the torque and speed control can be maintained in the whole speed range.

The schematic diagram of conventional direct torque control of induction motor drive is shown in Fig 1 in this schematic diagram consists of a torque and flux hysteresis comparators (T, Ψ), the reference values of torque and flux (T_e^*, Ψ_s^*), voltage vector sector selection, torque and flux estimators (Ψ_s, T_e), induction motor, real speed value (ω_r), stator flux angle $\theta_e(k)$, and voltage source inverter (VSI).

A. Source Inverter (VSI)

The 2-level and 3-phase VSI is shown in Fig.2., it has eight possible voltage space vectors, in this six active voltage vectors (UI-U6) and two zero voltage vectors (U7,U8), according to the combination of the switching modes are S_a, S_b, and S_c. When the upper part of switches is ON, then the switching value is '1' and when the lower switch is ON, then the switching value is '0'.

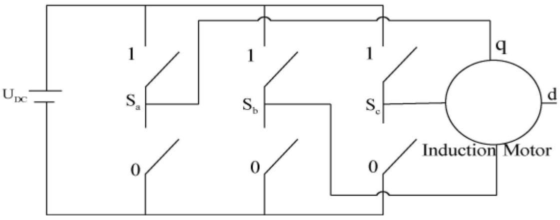


Fig. 2. Schematic diagram of voltage source inverter.

The stator voltage vector is equation (6)

$$\bar{U}_{s,k}= (2/3)U_{DC}\ [\ S_a + aS_b + a^2S_c\ ] \quad (6)$$

Where U_{DC} is the dc link voltage of inverter, $a=e^{j2\Pi/3}$

The eight possible voltage vector switching configuration is shown in Fig.3.

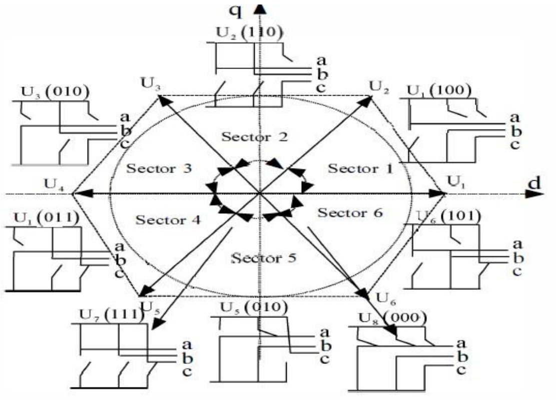


Fig 3. Switch Configuration of VSI

B. Direct Flux Control

The implementation of the DTC scheme requires torque and flux linkage computation and generation of vector switching states through a feedback control of the flux and torque directly without inner current loops. The stator flux in the stationary reference frame (d^S - q^S) can be estimated as [10]:

$$\bar{\Psi}^s_{ds} = \int(U^s_{ds} - i^s_{ds}R_s)dt \quad (7)$$

$$\bar{\Psi}^s_{qs} = \int(U^s_{qs} - i^s_{qs}R_s)dt \quad (8)$$

The estimated stator flux, $\overline{\Psi}_s$, is given by:

$$\overline{\Psi}_s=\sqrt{(\ \overline{\Psi}^s{}_{ds}{}^2+\ \overline{\Psi}^s{}_{qs}{}^2)} \qquad (9)$$

The change in input to the flux hysteresis controller can be written as:

$$\Delta\Psi_s = \Psi^*{}_s - \Psi_s \qquad (10)$$

A stator flux error ($\Psi^*{}_s$ - Ψ_s), thus determines which voltage vector has to be called, which is converted to the error state signal 'Ψ' using hysteresis flux controller with $\Delta\Psi_s$ hysteresis band. The flux hysteresis loop controller has 2-level of digital output Ψ, according to the following relation shown in Table 1.

Table 1. Switching Logic for Flux Error

State	Flux Hysteresis (Ψ)
$(\Psi_s{}^*-\Psi_s) > \Delta\Psi_s$	1
$(\Psi_s{}^*-\Psi_s) < -\Delta\Psi_s$	-1

C. Direct Torque Control

The electromagnetic torque error is produced through torque hysteresis controller to produce error state signal Te as shown in Table 3. The torque hysteresis loop control has three levels of digital output, which have the following relations is shown in Table 2.

Table 2. Switching Logic for Torque Error

State	Torque Hysteresis (T)
$(T_e{}^*-T_e) > \Delta T_e$	1
$-\Delta T_e < (T_e{}^*-T_e) < \Delta T_e$	0
$(T_e{}^*-T_e) < -\Delta T_e$	-1

when the torque hysteresis band is T=1 increasing torque, when T=O means torque at zero and T=-1 decreasing the torque. The instantaneous electromagnetic torque and angle in terms of stator flux linkage is given in equation (11), (12).

$$T_e= (3/2)(P/2)(\ \Psi^s{}_{ds}\, i^s{}_{qs} - \Psi^s{}_{qs}\, i^s{}_{ds}) \qquad (11)$$

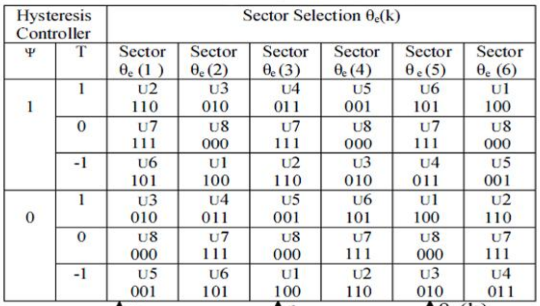
$$\theta_e(k)= \tan^{-1}(\ \overline{\Psi}^s{}_{qs} /\ \overline{\Psi}^s{}_{ds}) \qquad (12)$$

The change in electromagnetic torque error can be written as:

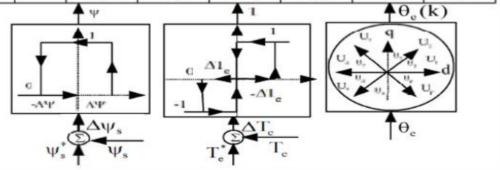
$$\Delta T_e = T^*{}_e - T_e \qquad (13)$$

Finally the stator output voltage is applied based on the selection of the switching states from voltage vector selector table. The switching states are selected based on whether the stator flux and torque need to be decreased or increased and also on the stator flux angle position.

Table 3. Voltage Vector Selection



Hysteresis Controller		Sector Selection $\theta_e(k)$					
Ψ	T	Sector $\theta_e(1)$	Sector $\theta_e(2)$	Sector $\theta_e(3)$	Sector $\theta_e(4)$	Sector $\theta_e(5)$	Sector $\theta_e(6)$
1	1	U2 110	U3 010	U4 011	U5 001	U6 101	U1 100
	0	U7 111	U8 000	U7 111	U8 000	U7 111	U8 000
	-1	U6 101	U1 100	U2 110	U3 010	U4 011	U5 001
0	1	U3 010	U4 011	U5 001	U6 101	U1 100	U2 110
	0	U8 000	U7 111	U8 000	U7 111	U8 000	U7 111
	-1	U5 001	U6 101	U1 100	U2 110	U3 010	U4 011



The voltage vector is selected using torque or flux need to be increased or decreased comes from the three level and two level hysteresis comparators for torque and stator flux respectively. The Fig.5, illustrates the 2-hysteresis optimized voltage vector in six sectors and which are selected from six active and two zero voltage vector switching configurations, using the voltage vector selection table is shown in Table 3. The voltage vectors are U_k, U_{k+1} or U_{k-1} is used for increasing flux (IΨ), U_{k+2} , U_{k+3} and U_{k-2} is used for flux decreasing (DΨ), U_k, U_{k+l}, U_{k+2} is used for torque increasing (IT), and Uk+3, Uk-2, and Uk-1 use for torque decreasing (DT) [7].

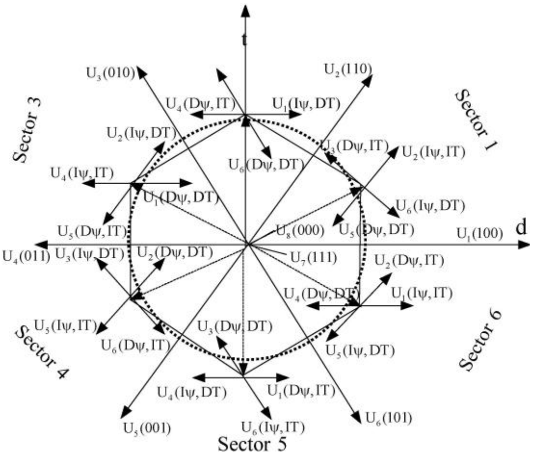


Fig 4. Space Vector in six sectors of flux plane

If UO or U7 is selected, the rotation of flux is stopped and the torque decreases whereas the amplitude of flux remains unchanged, with this type of torque and flux hysteresis comparator, we can control and maintain the end of the voltage vector flux within a circular zigzag path in a ring.

IV. PI AND FUZZY LOGIC CONTROLLER

The combination of proportional and integral terms is important to increase the speed of the response and also to eliminate the steady state error. A PI controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error in outputs by adjusting the process control inputs. These values can be interpreted in terms of time: P depends on the present error, I depends on the accumulation of past errors, based on current rate of change.

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain constant. The proportional gain is given by:

$$P_{out}=K_p e(t)$$

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PI controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain K_i and added to the controller output. The integral value is given by:

$$I_{out}=K_i \int e(\tau)\, d\tau$$

The fuzzy logic control is one of the controller in the artificial intelligence techniques. Fig.1 and Fig.5 and Fig.6 and Fig.7 shows the schematic model of the DTC of IMD and FLC based SR. In paper the Mamdani type FLC is using. In the DTC of IMD using conventional PI controller based SR are requires the precise mathematical model of the system and appropriate gain values of PI controller to achieve high performance drive. Therefore, unexpected change in load conditions would produce overshoot, oscillation of the IMD speed, long settling time, high torque ripple, and high stator flux ripples. To overcome this problem, a fuzzy control rule look-up table is designed from the performance of speed response of the DTC of IMD. According to the speed error and change in speed error, the proportional gain values are adjusted on-line [8].

A FLC converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert knowledge or experience database. Firstly, the input speed $\Delta\omega_r(k)$ and the change in error speed $\Delta\omega_r^*$ (k) have been placed of the speed to be the input variables of the FLC. Then the output variable of the FLC is presented by the control reference torque T_e^*. To convert these numerical variables into linguistic variables, the following five fuzzy levels or sets are chosen as: NL (negative large), NS (negative small), ZE (zero), PS (positive small), and PL (positive large).

The fuzzy controller is characterized as follows:

1) Five fuzzy sets for each input and output variables,
2) Fuzzification using continuous universe of discourse,
3) Implication using Mamdani's 'min' operator,
4) De-fuzzification using the 'centroid' method.

Fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. Fuzzification is the process of changing a real scalar value into a fuzzy value.

De-fuzzification is the process of producing a quantifiable result in fuzzy logic, given fuzzy sets and corresponding membership degrees. It is typically needed in fuzzy control systems.

Database: the database stores the definition of the membership Function required by fuzzifier and defuzzifier.

A. Fuzzy Variables

In the crisp variables of the speed error and change in speed error are converted into fuzzy variables $\Delta\omega_r(k)$ and $\Delta\omega_r^*(k)$ that can be identified by the level of membership functions in the fuzzy set. The fuzzy sets are defined with the triangular membership functions.

B. Fuzzy Control Rules

In the fuzzy membership function there are two input variables and each input variable have five linguistic values, so 5x5=25 fuzzy control rules are in the fuzzy reasoning is shown in TABLE. 4, and flowchart of FLC is shown in Fig.7.

Fig 5 The Structure of Fuzzy Logic

Table 4. Fuzzy Control Rules

$\Delta\omega^*_r(k)$ / $\Delta\omega_r(k)$	NL	NS	ZE	PS	PL
NL	NL	NL	NL	NS	ZE
NS	NL	NL	NS	ZE	PS
ZE	NL	NS	ZE	PS	PL
PS	NS	ZE	PS	PL	PL
PL	ZE	PS	PL	PL	PL

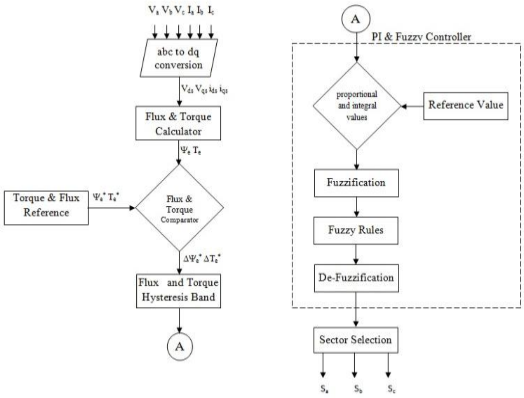


Fig 7. Flowchart of fuzzy logic controller

V. SIMULATION RESULT

The simulation of the proposed system with direct torque control of induction motor drive is carried out in MATLAB and shown in fig. 8. The simulation results of conventional PI control and fuzzy logic controller based speed regulator is shown in Fig 9.

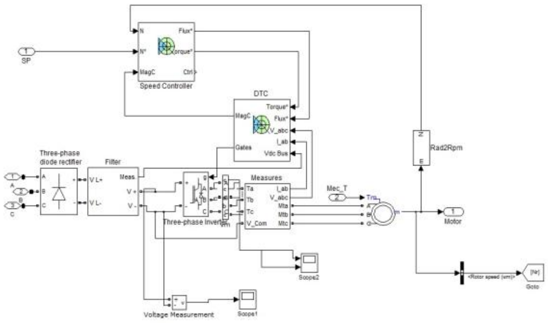
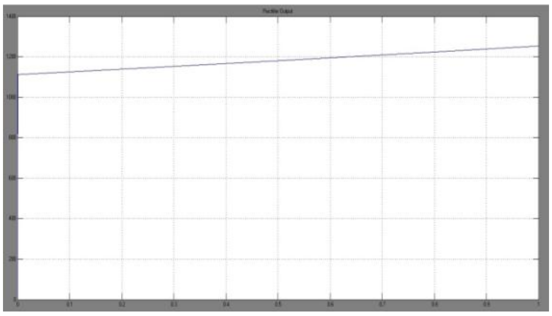
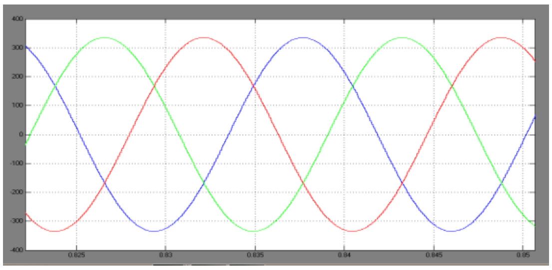


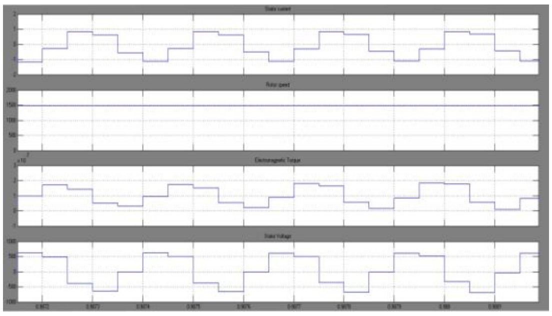
Fig 8. Simulation diagram of DTC of IMD



(a) Rectifier Output



(b) Inverter Output



(c) Stator Current, Rotor Speed, Torque and Stator Voltage

Fig 9. (a) Rectifier Output, b) Inverter Output, (c) Stator Current, Rotor Speed, Torque and Stator Voltage.

VI. CONCLUSION

In this project a simple approach for torque, flux, and speed regulating of direct torque controlled Induction Motor Drive using both conventional PI and Fuzzy Logic Controller has been presented, among both of them Fuzzy Logic Controller based Speed Regulation is superior for the low torque, stator flux ripples, and maintained rated speed under transient and steady state operating conditions. Also the torque and flux can be directly controlled with the inverter voltage vector using space vector modulation technique. Two independent torque and flux hysteresis controllers are used in order to control the limits of the torque and stator flux ripples. The simulation results of the direct torque control of Induction Motor Drive using both conventional PI and Fuzzy Logic Controller based Speed Regulation is presented, and simulation results shows the Fuzzy Logic Controller based Speed Regulation is superior than conventional PI control based Speed Regulation because of high performance, low torque and stator flux ripples, and rated speed under transient and steady state operating conditions.

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